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Radiation Detectors and Front-End Electronics

Helmuth Spieler

Physics Division
Lawrence Berkeley National Laboratory

email: spieler@LBL.gov

These course notes and additional tutorials at
http://www-physics.lbl.gov/~spieler

More detailed discussions in
H. Spieler: Semiconductor Detector Systems, Oxford University Press, 2005

WHY?

Radiation is the only observable in processes that occur on a scale that is either too brief or too small to be observed directly.

Originally developed for atomic, nuclear and elementary particle physics, radiation detectors now are applied in many diverse areas of science, engineering and everyday life.

Progress in science is driven not just by the interplay of theory and experiment, but also by breakthroughs in instrumentation.

Types of Radiation:

a) charged particles

electrons, protons, atomic nuclei

+ many elementary particles

b) neutral particles

neutrons

+ many elementary particles

c) photons

light	~ eV
x-rays	~ keV
gamma rays	~ MeV

Energies of nuclear particles are usually expressed in eV, i.e. the energy gained by an electron traversing a potential of 1 V.

Photons are very high frequency electromagnetic radiation

Same physics as for radio frequencies, but energy quantization is measurable.

Energy quantization: $E = \hbar\omega$,

where the Planck constant $\hbar \equiv \dfrac{h}{2\pi} = 1.055 \cdot 10^{-34}$ J s

Examples: RF (1.6 MHz) $\omega = 10^{7} \Rightarrow E \approx 10^{-27}$ J,

so the power of 1 quantum per second is 10^{-27} W

Compare with electronic noise:

0 dB noise figure and 1 Hz bandwidth: $P_n \approx 2 \cdot 10^{-20}$ W

visible light $\omega = 10^{15} \Rightarrow E \approx 10^{-19}$ J

1 eV = $1.609 \cdot 10^{-19}$ J, so $\hbar = 6.583 \cdot 10^{-16}$ eV s

Visible light is in the range of 1 eV.

Emphasis of this course: Detection of individual particles or photons

The development of detector systems is an interdisciplinary mix of physics and electronics.

For example, understanding of a modern tracking detector in high-energy physics or a medical imaging system requires knowledge of

- solid state physics
- semiconductor device physics
- semiconductor fabrication technology
- low-noise electronics techniques
- analog and digital microelectronics
- high-speed data transmission
- computer-based data acquisition systems

Course Contents

Many different types of detectors are used for radiation detection.

Nearly all rely on electronics.

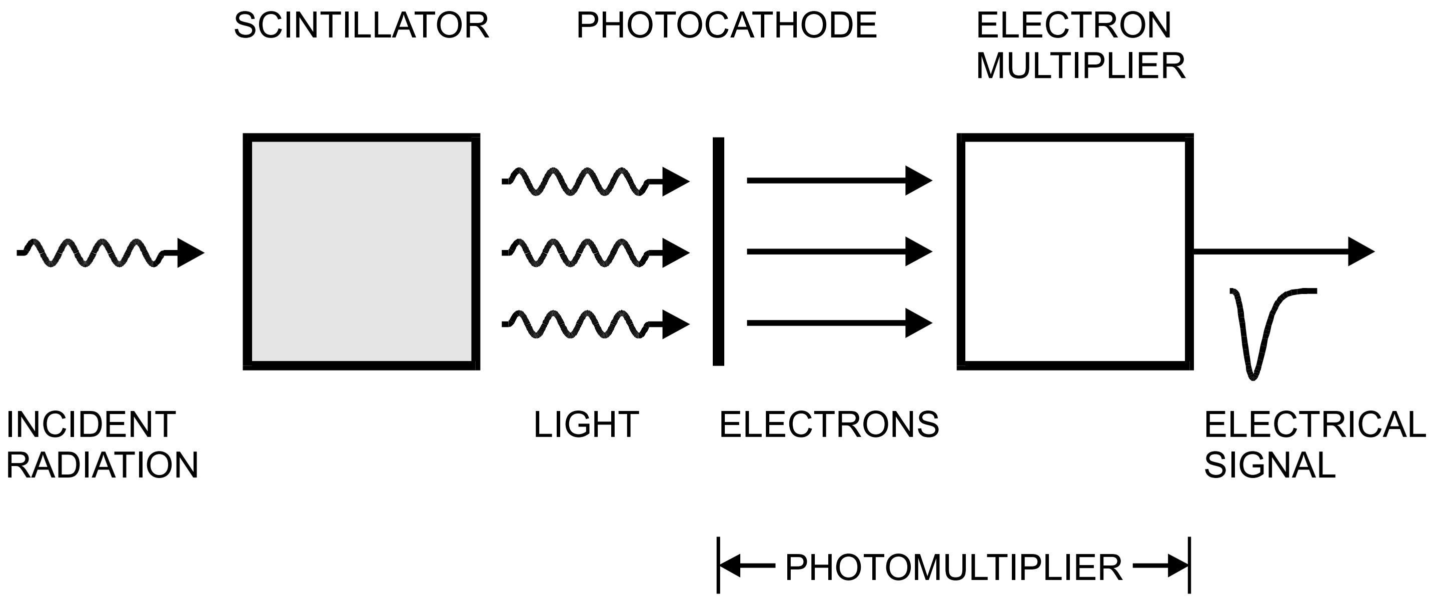
Although detectors appear to be very different, basic principles of the readout apply to all.

- The sensor signal is a current.
- The integrated current $Q_S = \int i_S(t)dt$ yields the signal charge.
- The total charge is proportional to the absorbed energy.

Readout systems include the following functions:

- Signal acquisition
- Pulse shaping
- Digitization
- Data Readout

Example: Scintillation Detector

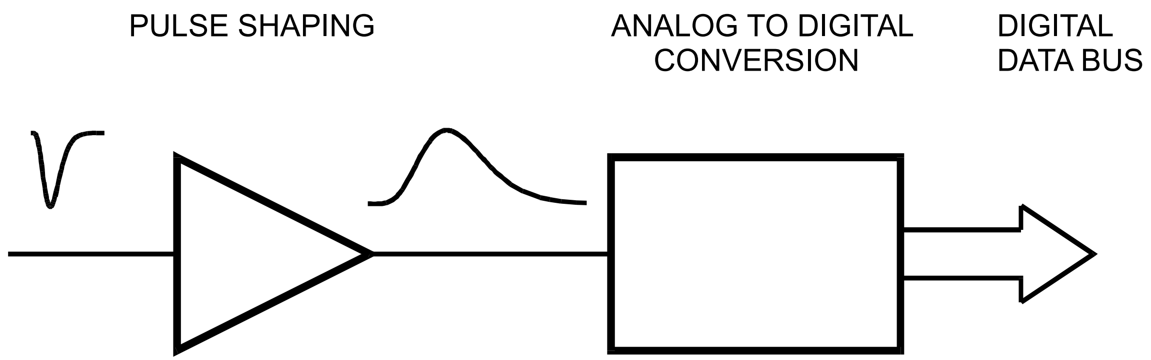


number of photons
$\propto$ absorbed energy

number of photoelectrons
$\propto$ absorbed energy

charge in pulse
$\propto$ abs. energy

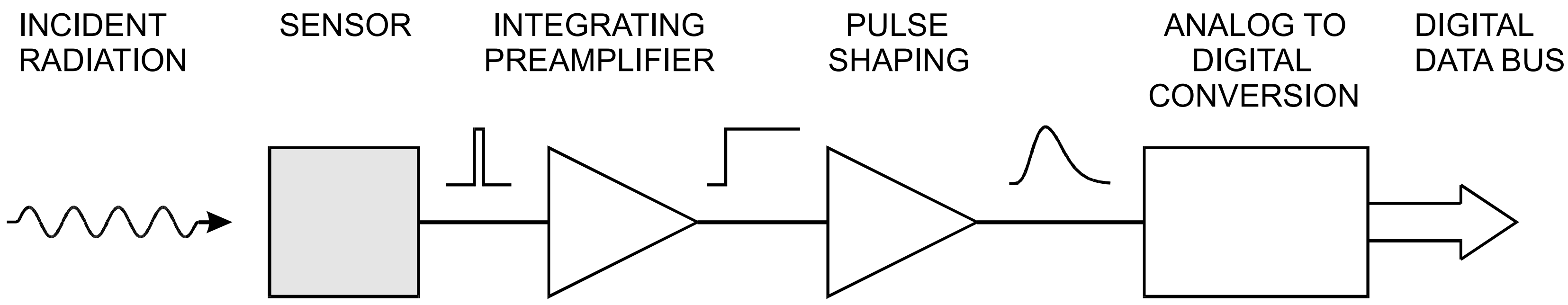
Readout



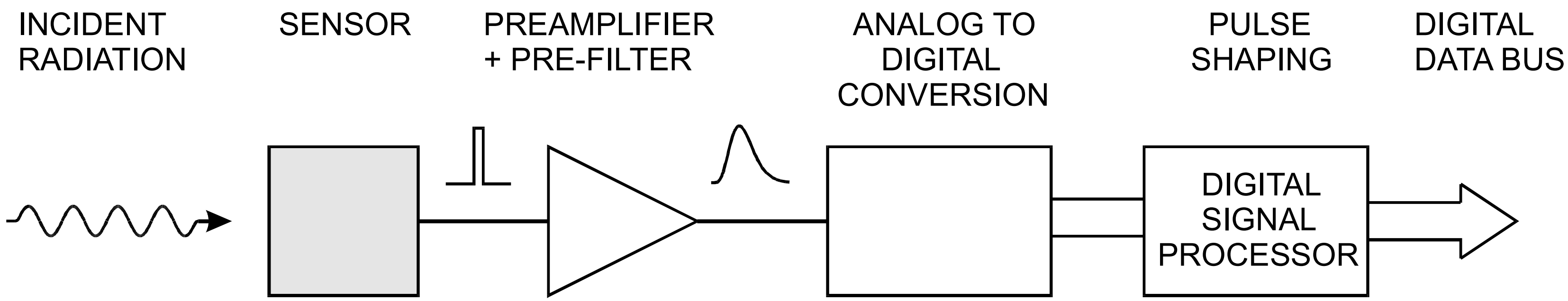
charge in pulse
$\propto$ absorbed energy

pulse height
$\propto$ absorbed energy

1. Basic Functions of Front-End Electronics

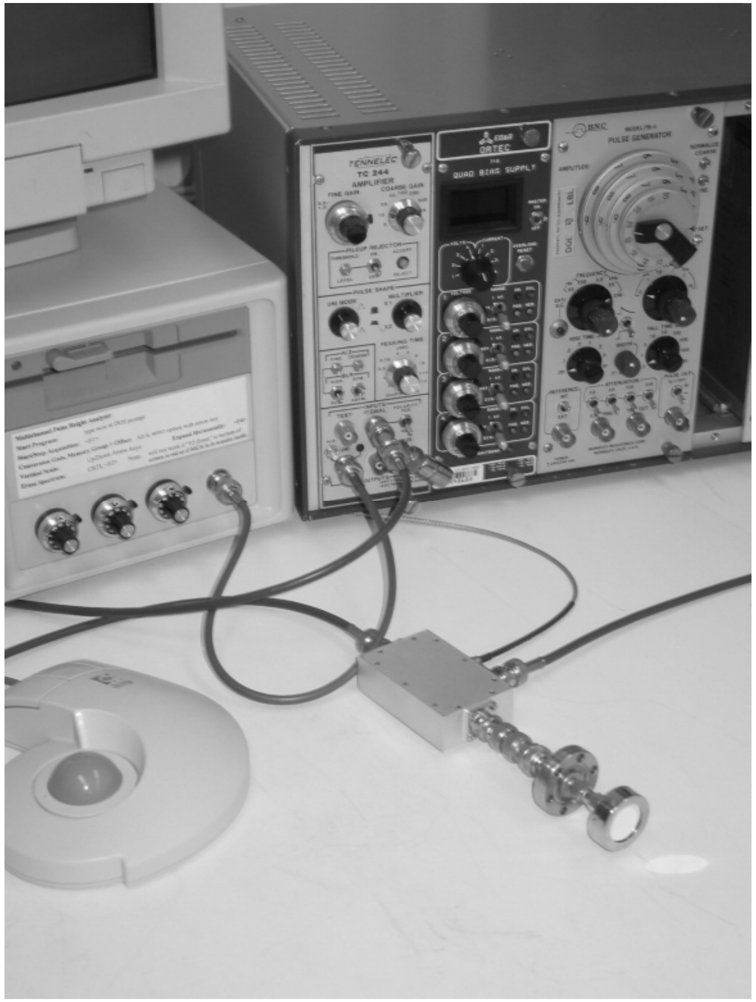


Pulse shaping can also be performed with digital circuitry:



Many Different Implementations

“Traditional” Si detector system
for charged particle measurements



Tracking Detector Module (CDF SVX)
512 electronics channels on 50 μm pitch

Spectroscopy systems highly optimized!

By the late 1970s improvements were measured in %.

Separate system components:

1. detector
2. preamplifier
3. amplifier
    - adjustable gain
    - adjustable shaping
        - (unipolar + bipolar)
    - adjustable pole-zero cancellation
    - baseline restorer

Beam times typ. few days with changing configurations, so equipment must be modular and adaptable.

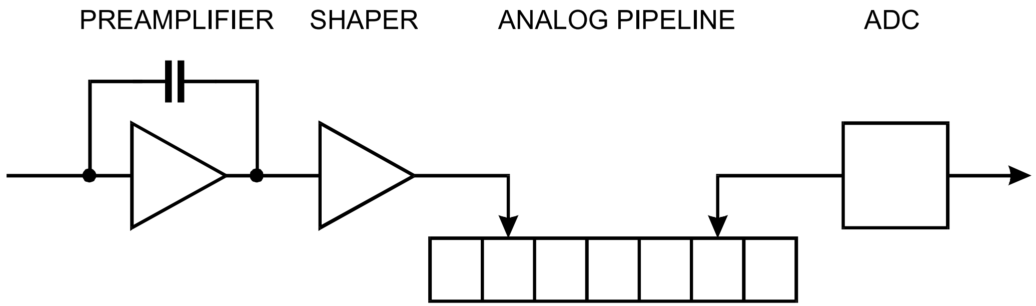
Today, systems with many channels are required in many fields.

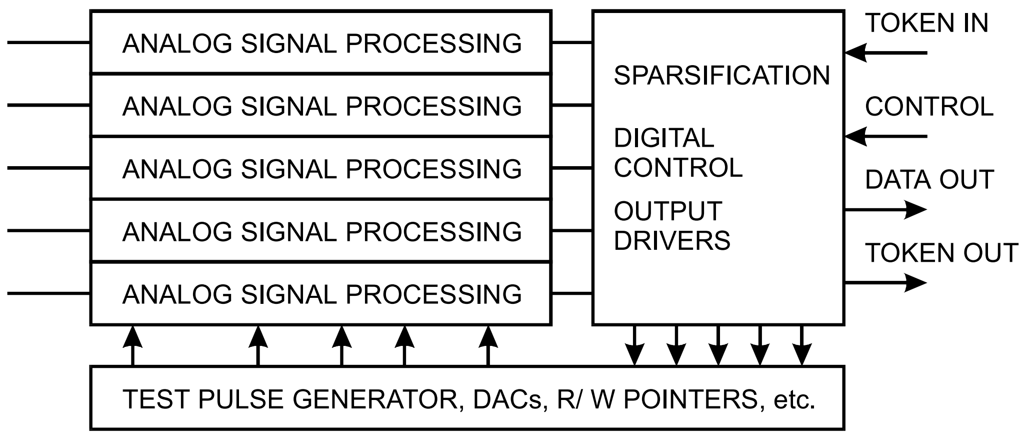
In large systems power dissipation and size are critical, so systems are not necessarily designed for optimum noise, but *adequate* noise, and circuitry is tailored to specific detector requirements.

Large-Scale Readout Systems

Example: Si strip detector

On-chip Circuits

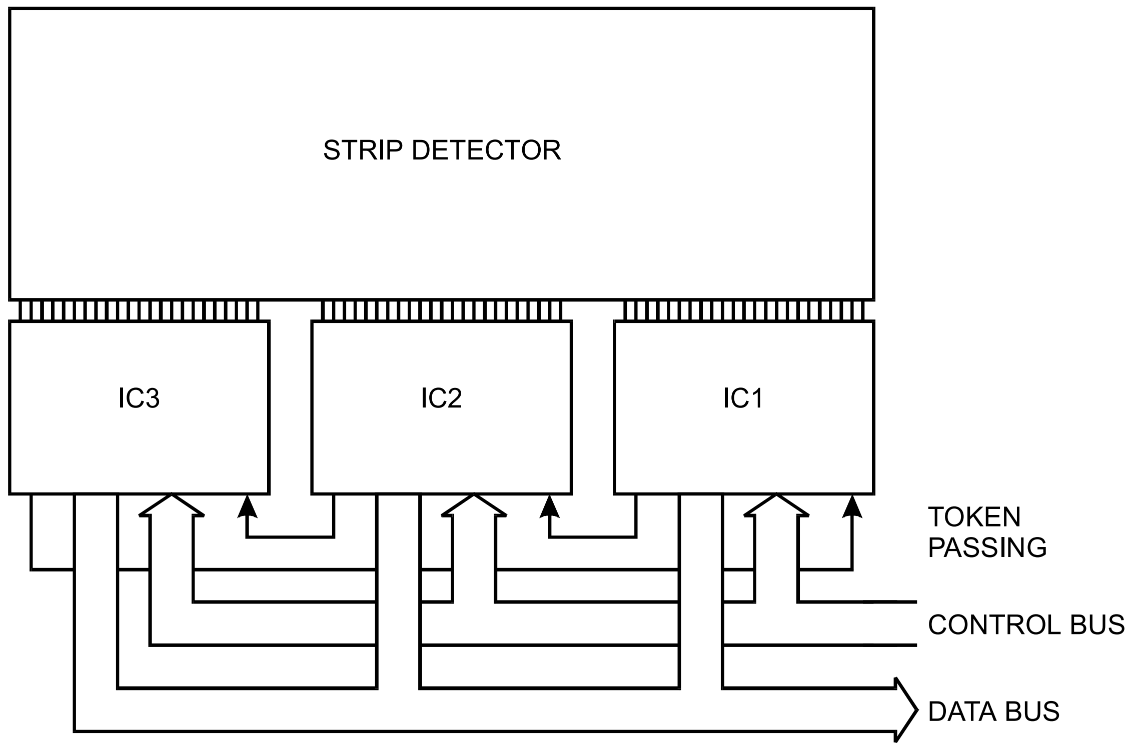




Inside a typical readout IC:

128 parallel channels of analog front-end electronics
Logic circuitry to decode control signals, load DACs, etc.
Digital circuitry for zero-suppression, readout

Readout of Multiple ICs



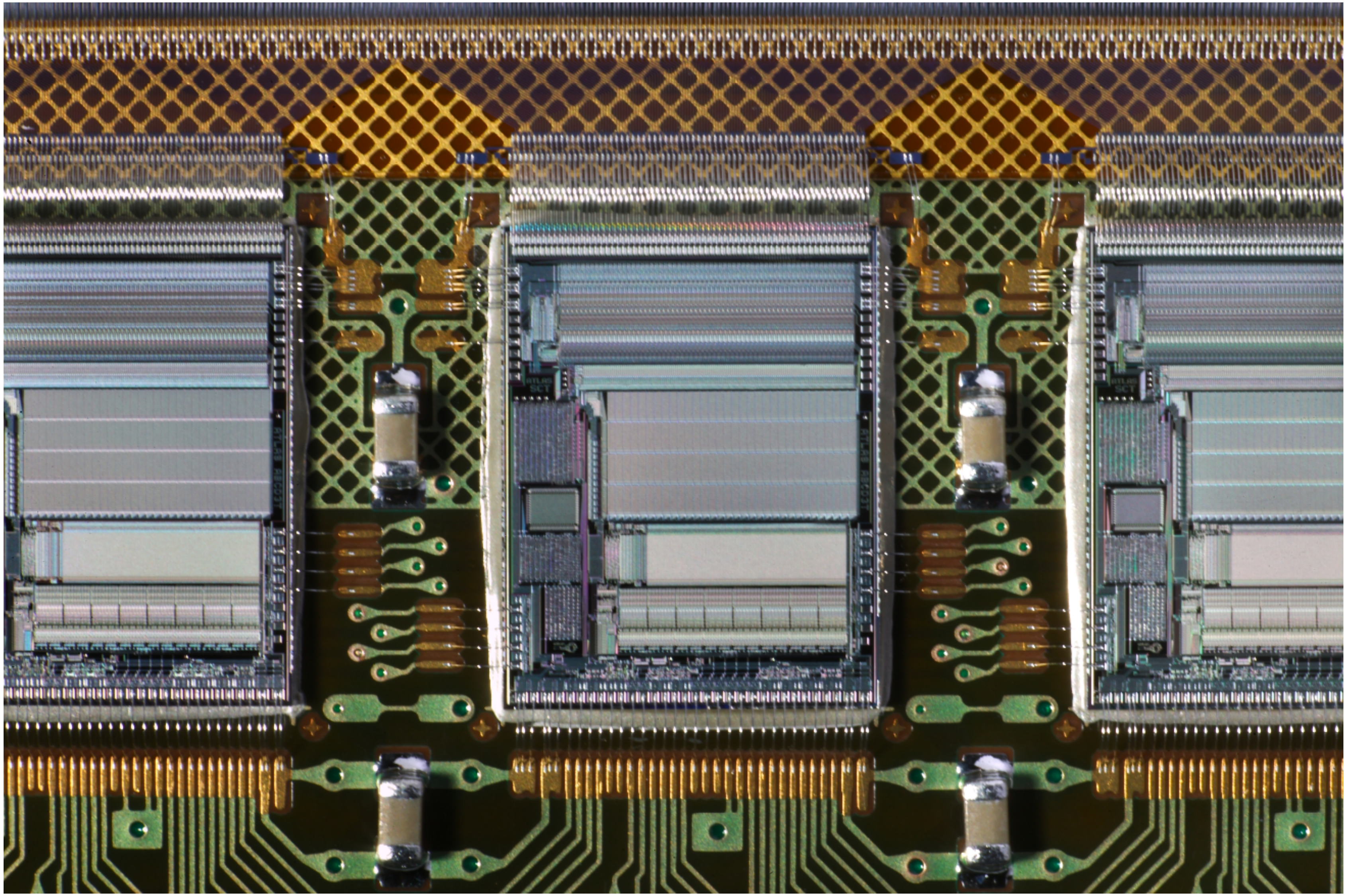
IC1 is designated as master.

Readout is initiated by a trigger signal selecting appropriate time stamp to IC1.

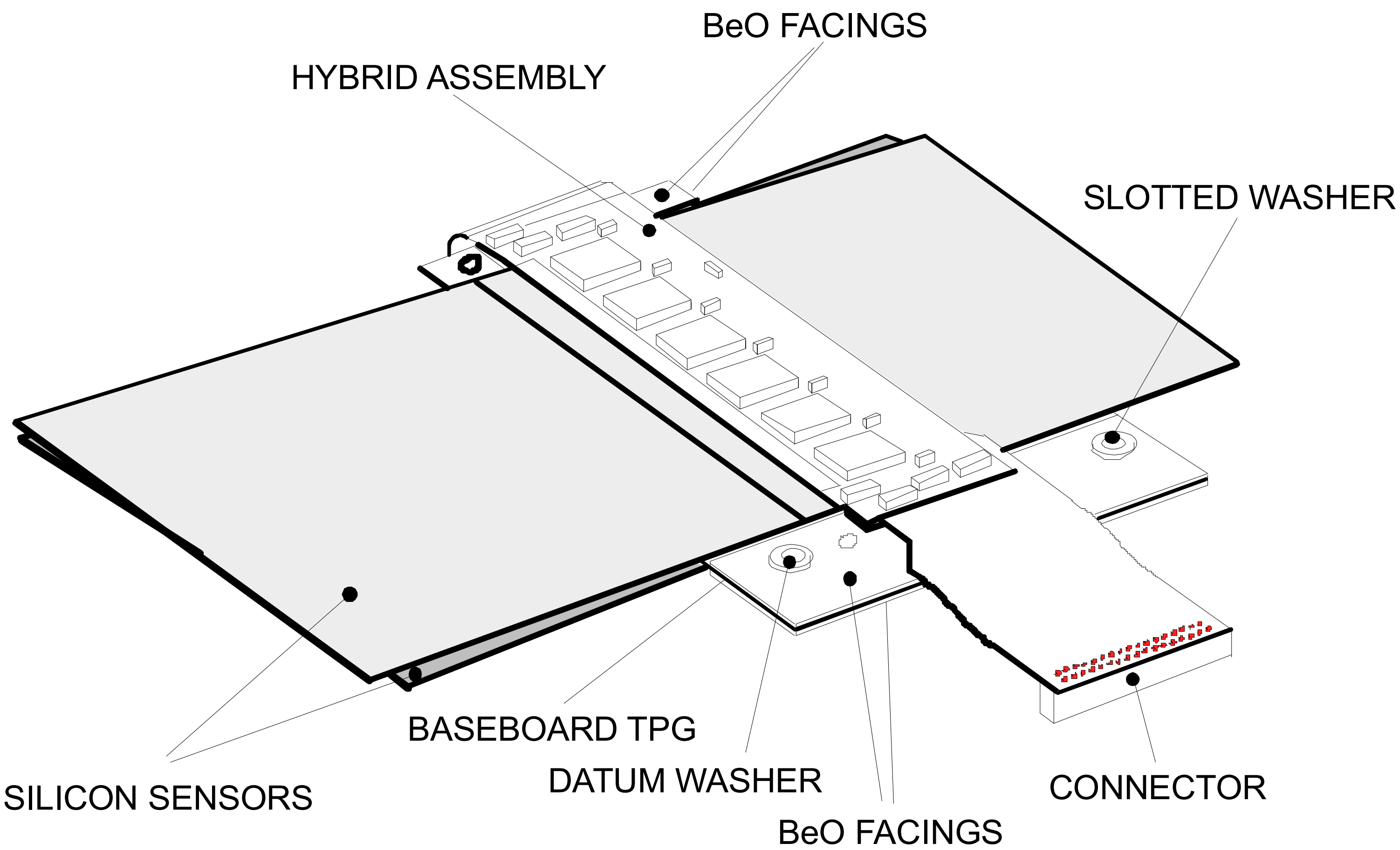
When all data from IC1 have been transferred, a token is passed to IC2.

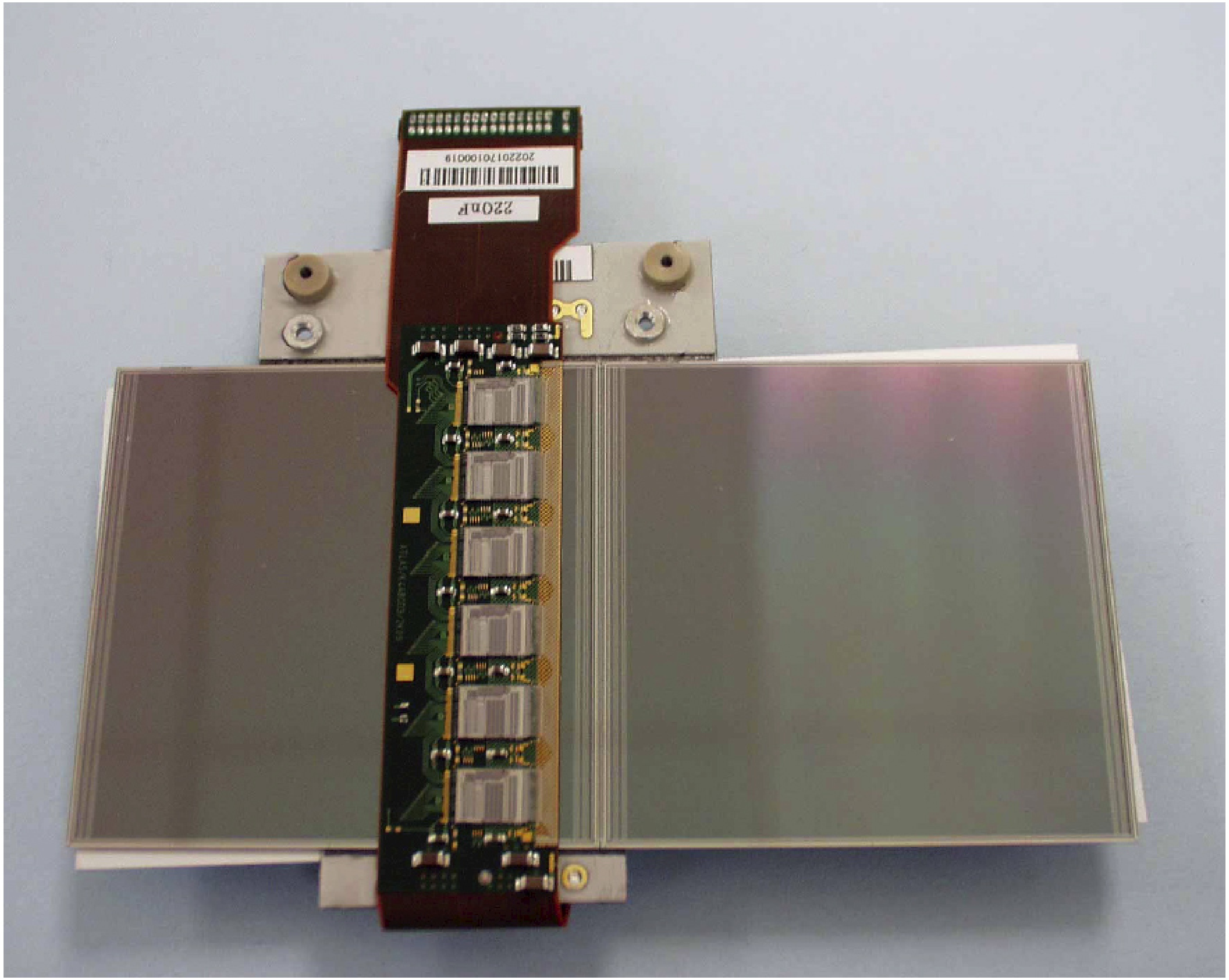
When IC3 has finished, the token is passed back to IC1, which can begin a new cycle.

ATLAS Silicon Strip system (SCT): ABCD chips mounted on hybrid

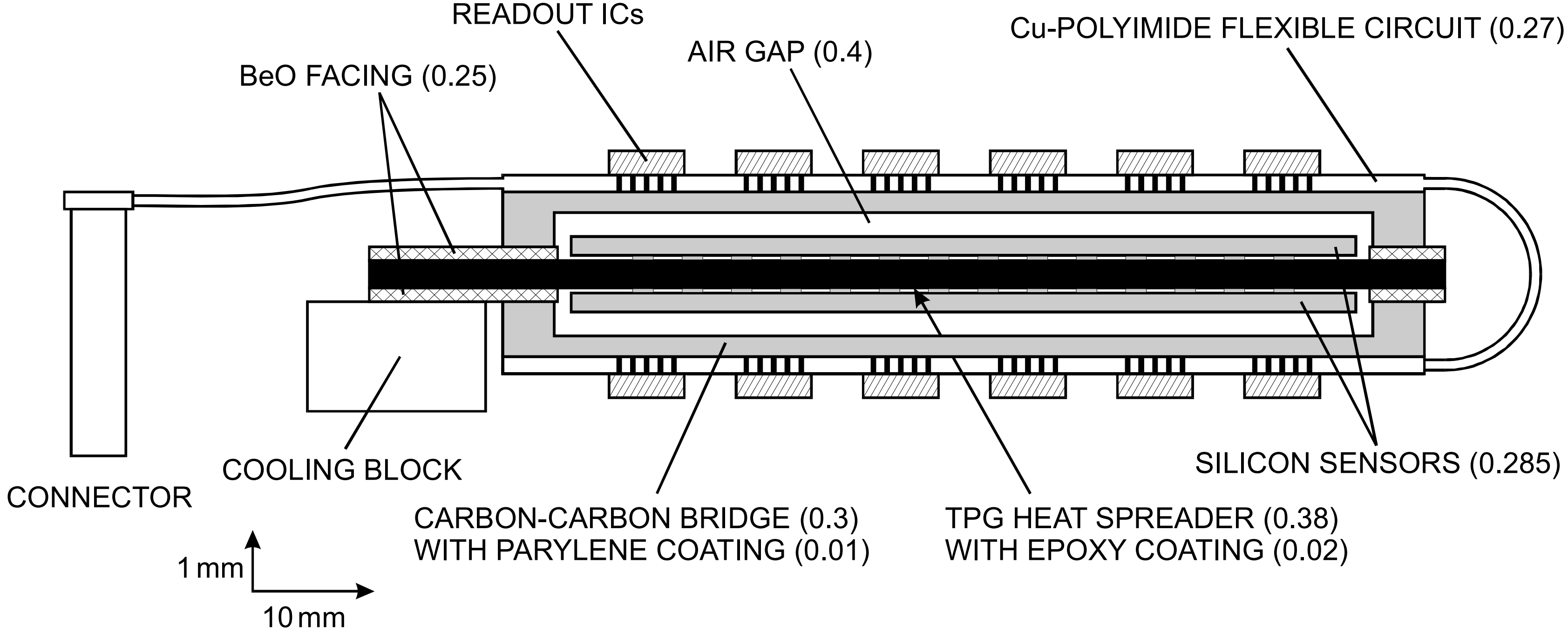


ATLAS SCT Detector Module





Cross Section of Module



Design criteria depend on application

1. Energy resolution
2. Rate capability
3. Timing information
4. Position sensing

Large-scale systems impose compromises

1. Power consumption
2. Scalability
3. Straightforward setup + monitoring
4. Cost

Technology choices

1. Discrete components – low design cost
fix “on the fly”
2. Full-custom ICs – high density, low power, but
better get it right!

Successful systems rely on many details that go well beyond “headline specs”!